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CCI-AWU IMPRES
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ESA Contract No. 4000150476/25/I-LR



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CCI-AWU IMPRES (Climate Change Initiative – Anthropogenic Water Use IMProved RESolution)

Deliverable 2

Report on data collection and EO datasets preparation



Date	Issue	Section	Page	Comment
August 2026	1.0			
October 2026	2.0			

Control Document

Process	Name	Date
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1. Introduction

1.1 The CCI-AWU IMPRES project

The consolidation of the remote sensing of irrigation water use (IWU), which closely approximates the total anthropogenic water use (AWU) (Abbot et al., 2019), led to the perspective of developing satellite-based IWU datasets to foster climate studies. This circumstance, together with a possible declaration of AWU as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS), has been the driver of the Climate Change Initiative (CCI) AWU precursor project, started at the end of 2023. Its first phase targeted major irrigation hotspots worldwide, namely the Contiguous United States (CONUS), India, and the Ebro and Murray-Darling basins in Spain and Australia, respectively. As an output of the project, regional datasets of long-term and coarse resolution irrigation estimates from space have been released (Laluet et al., 2025).

The climate perspective of interest in the CCI-AWU project imposed the use of coarse resolution satellite retrievals, which can ensure at least 20 years of observations. As expected, some difficulties were found in getting the irrigation signal from coarse-resolution (0.25°) soil moisture and evaporation data and, hence, an important conclusion of the CCI-AWU project is the need to move to higher resolution products. As a consequence, the main purpose of the IMPRES (IMProved RESolution) phase is to investigate the potential of using improved resolution soil moisture and evaporation products to enhance the accuracy of the IWU datasets maintaining a climate perspective (20+ years).

Three main activities are foreseen:

- IWU product development with new high-resolution (10 km and 1 km) soil moisture products;
- IWU products assessment with the comparison against in situ data, modelling and other EO-based IWU products;
- Use Cases for assessing the impact of the IWU product in applications.

1.2 Scope of this report

This document aims at describing the study regions and all the data collected or generated (i.e., in situ reference irrigation, satellite retrievals and meteorological data) as part of WP200 of the CCI-AWU IMPRES project. The data have been collected in a project database for sharing among the team, with the primary goal of ensuring that all team members are using consistent data versions.

1.3 Applicable documents

- Proposal;
- D1. Project Management Plan (PMP).

2. Study regions and in situ data collection

The pilot regions were selected according to four main criteria: (1) the need to focus on highly irrigated areas; (2) the importance of representing diverse climatic, geophysical, and geomorphological conditions, as well as study areas of different spatial extents; (3) the availability of long-term in situ benchmark datasets to test and validate the project outputs; (4) keeping, if possible, test sites from the first phase of the project to highlight improvements potentially achievable through the novel outputs. Based on these criteria, the areas selected for the implementation of the AWU algorithms and modelling framework include the contiguous United States (CONUS), Europe with a specific focus on the Mediterranean area, and the Murray–Darling Basin in Australia. This section describes the main characteristics of the pilot areas and the in situ datasets collected at the different sites. All the collected data is stored in a OneDrive repository.

2.1 Contiguous United States (CONUS, US)

The contiguous United States (CONUS) were selected as a test region because of the large extent of their irrigated areas, which is well suited to the spatial sampling characteristics of the AWU products under development. Several subregions within CONUS have previously been identified as irrigation hotspots in studies investigating the detectability of irrigation signals from satellite observations (Lawston et al., 2017; Zaussinger et al., 2019).

Among these, California's Central Valley is particularly relevant, as it records some of the highest irrigation water withdrawal rates in CONUS. The region is characterised by diverse climatic conditions, ranging from a Mediterranean climate in the north to hot and cold semi-arid climates in the south (Zaussinger et al., 2019). Rice cultivation is widespread in the northern part of the valley, where fields are typically flooded throughout the growing season. The Nebraska High Plains represent another major irrigation hotspot. The western portion of this region is characterised by a cold semi-arid climate, which gradually transitions to humid continental conditions towards the east. Soybean and maize are the dominant crops, and centre-pivot irrigation systems are widely used throughout the area (Zaussinger et al., 2019).

These irrigation hotspots are clearly identifiable in the Global Map of Irrigated Areas (GMIA) dataset (Siebert et al., 2015) shown in Figure 2.1.

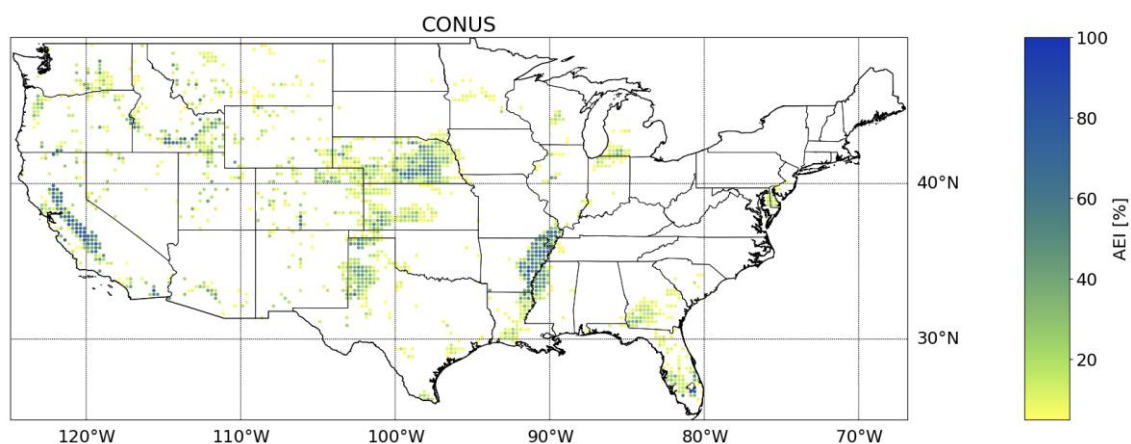


Figure 2.1: Percentage of area equipped for irrigation according to the GMIA (Global Map of Irrigated Areas) data set over the CONUS.

Information on irrigation dynamics across the contiguous United States (CONUS), including the extent of irrigated areas and the volume of water applied, was obtained from the Farm and Ranch Irrigation

Survey (FRIS) conducted by the National Agricultural Statistics Service (NASS) of the United States Department of Agriculture (USDA). Surveys referring to the years 2013 and 2018 were used in the first phase of the project; in the IMPRES phase, additional data referring to the last survey available, dated 2023, were collected.

The survey compiles data collected from approximately 35000 farms practising irrigation. The resulting database provides county-level aggregated information on irrigated areas and irrigation water withdrawals, disaggregated by crop type, water source, and irrigation method. It also includes additional metadata, such as the distinction between crops grown indoors, for example in greenhouses, and those cultivated outdoors.

Figure 2.2 presents state-level irrigation water withdrawals for the three years available. The data is organised in a .xlsx file.

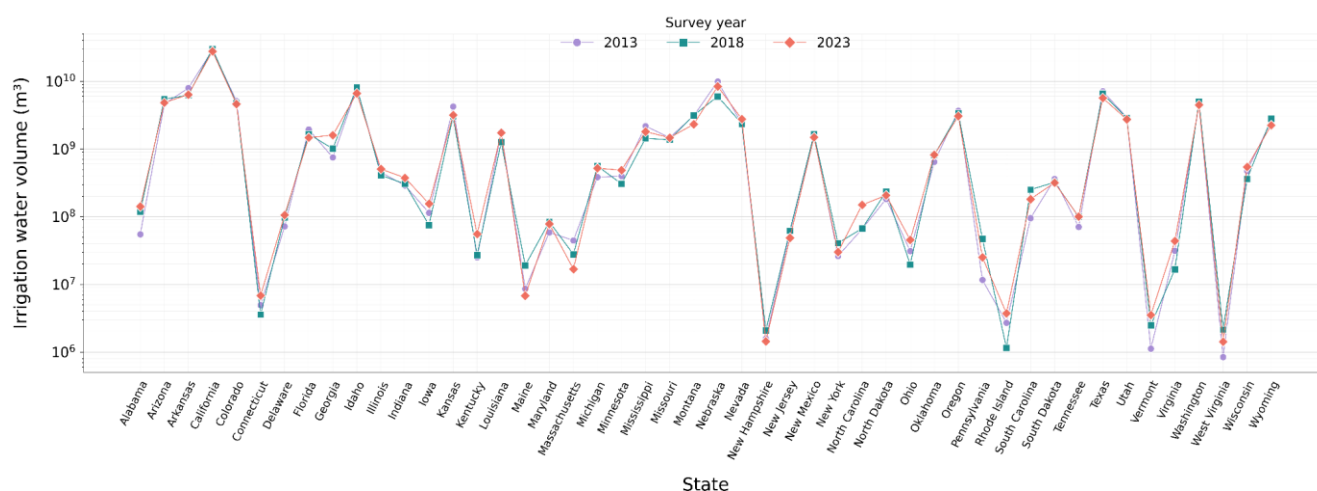


Figure 2.2: State-level irrigation water withdrawals to the FRIS 2013, 2018, and 2023.

2.2 Europe

Europe, with a focus on the Mediterranean portion where irrigation mostly occurs, was selected as a test region because of the presence of important irrigated areas in a context well-known to be a clear hotspot of climate change. Hence, making use of of satellite-based IWU estimates there is surely beneficial for the final purpose of the project, that is to support climate studies. The area was also chosen because of the nominal size of irrigated fields generally detectable. In fact, over Europe, improved resolution satellite retrievals are needed to properly reproduce irrigation dynamics (Dari et al., 2023; Zappa et al., 2022). This feature makes it possible to highlight the added value of the novel products developed within the IMPRES phase, involving 1 km experiments over targeted regions as well. Figure 2.3 shows the GMIA dataset over Europe, highlighting well-known irrigation hotspots, such as the Ebro basin and the Castilla-La Mancha region in Spain, the Po Valley in Italy, and the Kherson region in Ukraine, as well as over regionally relevant irrigated areas, such as parts of the Lower Danube along the Bulgaria–Romania border, among others.

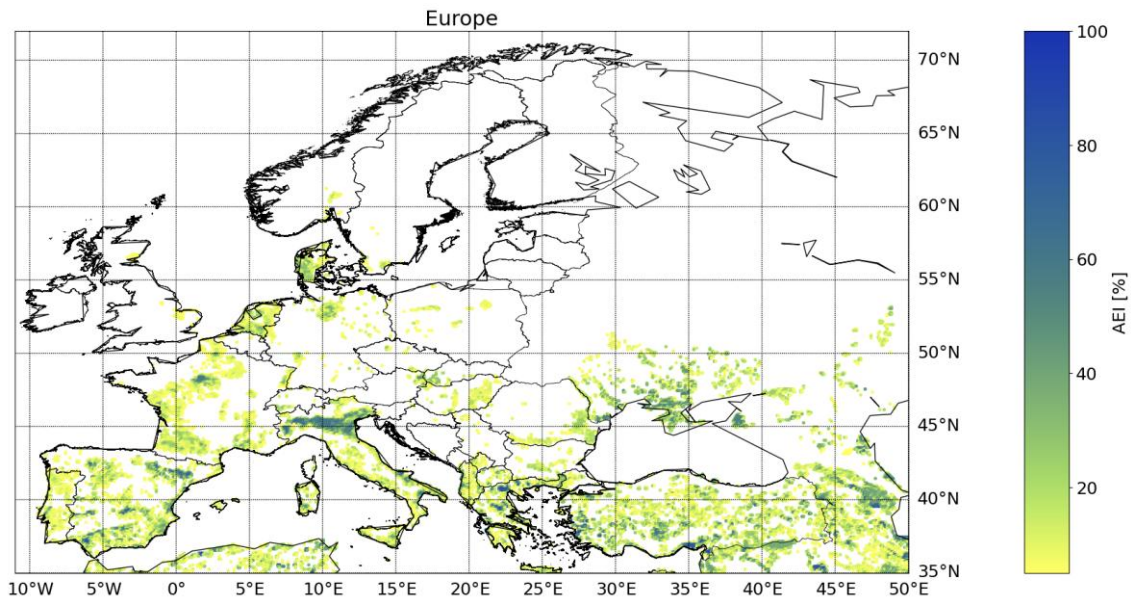


Figure 2.3: Percentage of area equipped for irrigation according to the GMIA (Global Map of Irrigated Areas) data set over Europe.

Reference IWU data were collected for test sites over the Ebro basin in Spain and the Po valley and the Umbria region in Italy.

2.2.1 Ebro basin, Spain

The Ebro basin covers an area of about 85362 km². Precipitation across the basin is highly variable in both space and time, with marked interannual fluctuations, particularly in the Mediterranean part of the region. Rainfall is mainly concentrated in spring and autumn, whereas summers are typically dry. The Ebro Basin supports extensive agricultural activity, including large irrigated areas where a range of irrigation techniques are used despite the surrounding semi-arid conditions. Runoff is generated primarily in the Pyrenees, stored in numerous reservoirs, and subsequently conveyed to agricultural areas through an extensive canal network. Irrigation strongly affects the hydrological functioning of the basin. Its influence on the main hydrological fluxes, including transpiration and streamflow, as well as on water-storage components such as soil moisture, therefore needs to be accurately quantified and represented. Concerning reference IWU records, data already used in the first phase of the project were extended in time within the IMPRES phase. They refer to four major agricultural districts located in a heavily irrigated area in the north-eastern part of the basin were selected for the validation of the CCI-AWU IMPRES irrigation products: Urgell, Algerri–Balaguer, Pinyana, and the Aragón and Catalonia district. The latter was divided into northern and southern sectors according to the structure of the irrigation canal network.

The selected areas extend across the regions of Aragón and Catalonia and are drained by the Cinca and Segre rivers and their tributaries. Irrigated fields are supplied through a canal network originating from a system of reservoirs located upstream of the agricultural areas. Benchmark irrigation rates were derived from records of water volumes flowing through the Aragón and Catalonia Canal, the Algerri–Balaguer Canal, the Urgell Canals, and the Pinyana Canal, whose locations are shown in Figure 2.4. The Pinyana Canal was built in the 13th century and is the oldest irrigation canal in Catalonia. It supplies approximately 13891 ha of irrigated land located north of Lleida. The canal diverts water from the Santa Anna Reservoir on the Noguera Ribagorçana River. Irrigation practices in this area remain predominantly traditional.

The Aragón and Catalonia Canal was inaugurated in 1906 and supplies approximately 98000 ha distributed across the provinces of Huesca, in Aragón, and Lleida, in Catalonia. It represents the second-largest irrigated area in the Ebro Basin and one of the largest in Spain. The canal is mainly

supplied by the Ésera River, a tributary of the Cinca River, through water stored in the Joaquín Costa Reservoir, also known as the Barasona Reservoir. The canal has a total length of approximately 124 km. Sprinkler irrigation is the most widespread technique, covering about 54% of the irrigated area, followed by drip irrigation at 28% and flood irrigation at 18%. For the purposes of this project, the area was divided into northern and southern districts according to the configuration of the canal network.

The Algerri–Balaguer Canal was constructed in the 1990s and supplies approximately 8000 ha located north of Lleida, between Alfarràs and Balaguer. Water is pumped from the Noguera Ribagorçana River. The construction of the hydraulic infrastructure was accompanied by a land-consolidation programme, through which the previously small and fragmented properties belonging to each owner were merged into single farms. This process facilitated the adoption of modern agricultural and irrigation practices. Drip irrigation is mainly used for fruit trees, whereas sprinkler irrigation is predominantly applied to arable crops.

The Urgell Canals were built in the late 19th century and supply approximately 70000 ha located on the left bank of the Segre River. Water is diverted from the Segre River and conveyed through a main canal approximately 144 km long. Owing to the age of this hydraulic infrastructure, irrigation practices in the area remain largely traditional, with gravity-fed flood irrigation being the dominant technique.

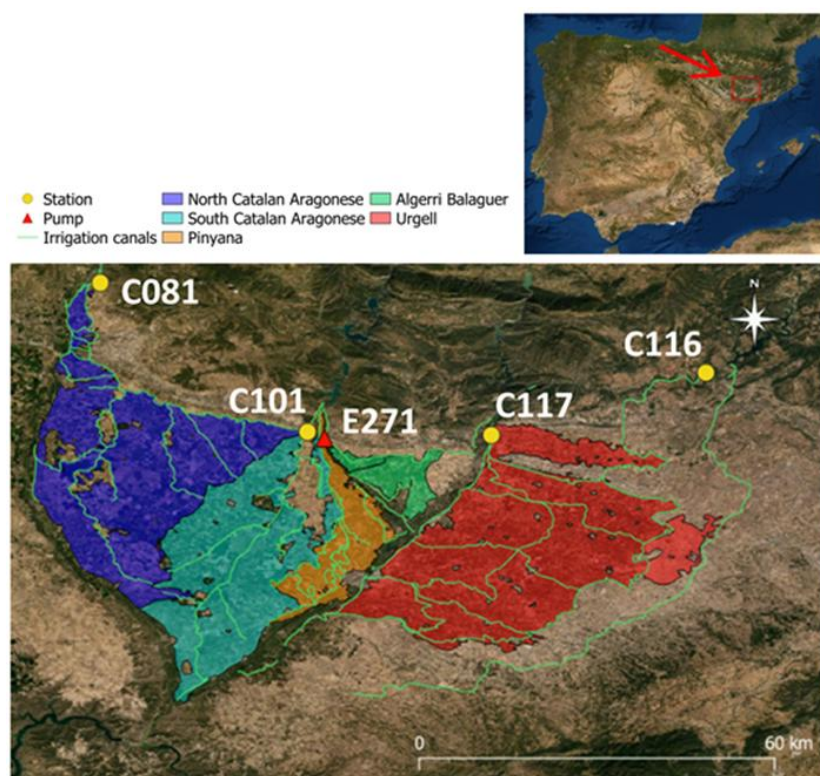


Figure 2.4: Overview of the irrigation infrastructure currently working on the selected area.

Benchmark irrigation data were derived from the volumes of water conveyed through the irrigation canals supplying the selected districts. These volumes were divided by the corresponding district areas to obtain irrigation amounts expressed as equivalent water depth. With the exception of the Pinyana district, the data were obtained from the Automatic Hydrological Information System of the Ebro River Basin (SAIH Ebro), available at: <http://www.saihebro.com/saihebro/index.php?url=/datos/canales>

Further details on the individual districts and the associated benchmark datasets are provided below:

- Urgell: The district covers an area of 887.62 km². Irrigation water volumes were derived from measurements recorded at stations C116 and C117, whose locations are shown in Figure 2.4. Conveyance losses of 30% were assumed, following Dari et al. (2020).
- Algerri–Balaguer: The district covers an area of 70.79 km². The benchmark data correspond to the volume of water pumped from the river and conveyed to the district, as monitored at station E271. Water losses of 10% were assumed, in accordance with Dari et al. (2020).
- Aragón and Catalonia: The northern and southern portions of the district cover areas of 657.04 km² and 504.48 km², respectively. Benchmark data for the northern sector were obtained from measurements recorded at station C081, whereas data for the southern sector were derived from station C101. Conveyance losses of 15% were assumed for both sectors, following Dari et al. (2020).
- Pinyana: The district covers an area of 149.74 km². As it is not included in the SAIH Ebro monitoring system, the available benchmark data consist of average monthly water consumption values provided by the district managers. Water losses of 30% were assumed, following Dari et al. (2020).

The benchmark data are organised in a NetCDF file.

As an example, the time series referring to the Urgell district is shown in Figure 2.5.

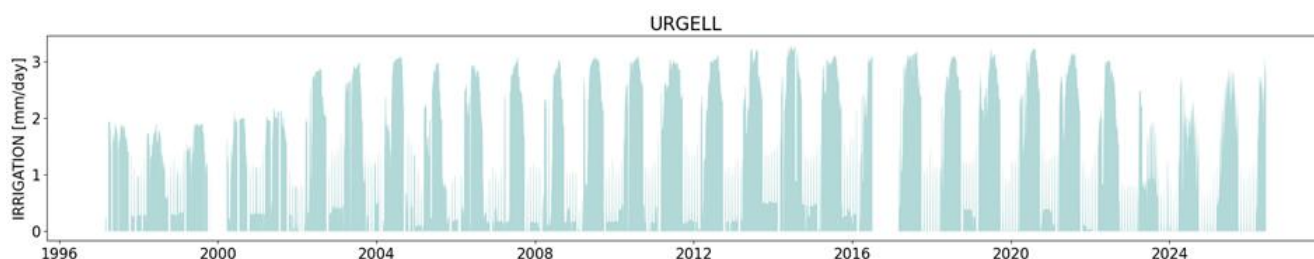


Figure 2.5: Daily benchmark irrigation over the Urgell district for the period 1997-today.

2.2.2 Po valley, Italy

The Po valley identifies the flat agricultural land of the Po river basin (Northern Italy), that refers to the longest Italian river (catchment area higher than 71000 km² and river length of about 652 km). The area is a critical hotspot for studying the impact of human activities on the water cycle, considering the key role of agricultural production and the increasing frequency of severe drought events (Camici et al., 2025). The size and spatial extent of the irrigated fields and districts in the Po valley are often not homogeneous, and agricultural plots are characterized by small extents due to complex historical processes (Massari et al., 2021). Main cultivated crops include general summer and winter crops, orchards, olive groves, and vineyards.

Two different data sources for benchmark IWU over the Po valley were considered. The first one consists of seasonal district-aggregated irrigation volumes based on self-declarations from SIGRIAN (Sistema Informativo Nazionale per la Gestione delle Risorse Idriche in Agricoltura) dataset, covering the period 2016-2021. An extraction over 92 irrigated districts whose area is > 50 km² was considered. To mitigate uncertainties due to the self-reported nature of the data, outliers, i.e., values beyond the 10th and 90th percentiles, were removed in advance. Data is provided by the Autorità di Bacino Distrettuale del Fiume Po (ADBPO). Fig. 2.6 shows the location of the pilot districts together with the distributions of seasonal district-aggregated IWU values across time.

The data are organised in a NetCDF file.

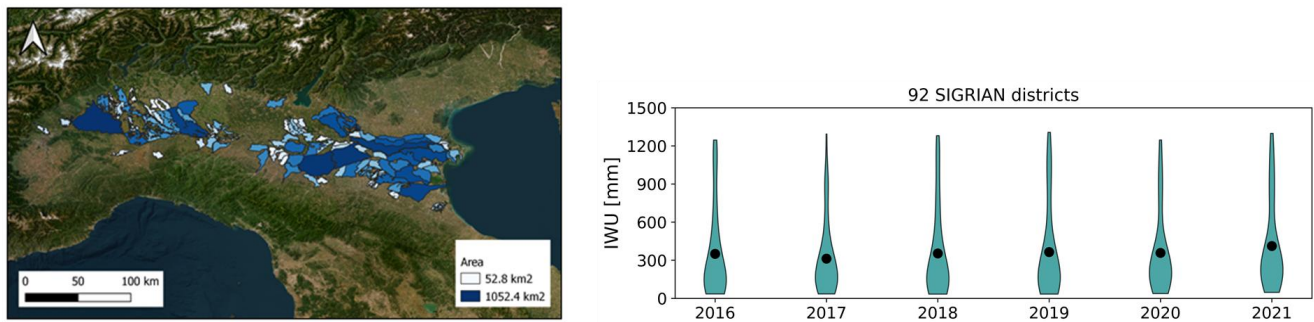


Figure 2.6: Location of the pilot SIGRIAN districts and reference seasonal IWU amounts.

The second data source consists of site-specific time series for two districts in the Faenza area (Emilia Romagna region), namely San Silvestro (2.9 km²) and Formellino (7.6 km²). Information on the main crops growing on the site can be collected from the project for crop classification through remote sensing (IColt, https://www.arpae.it/dettaglio_generale.asp?id=2824&idlivello=1599) led by the Regional Agency for Prevention, Environment and Energy of Emilia-Romagna (Arpae). Fruit trees are prevalent over the districts; in particular, peach trees and vineyards dominate the San Silvestro field while vineyards, kiwi, peach and apricot trees are mainly cultivated in the Formellino area. The water used for irrigation is available at daily time scale for the 4-year period 2016-2019 (see Fig. 2.7). The data, provided by CER (Canale Emiliano Romagnolo) was already used within the ESA Irrigation+ project.

The data are organised in a NetCDF file available.

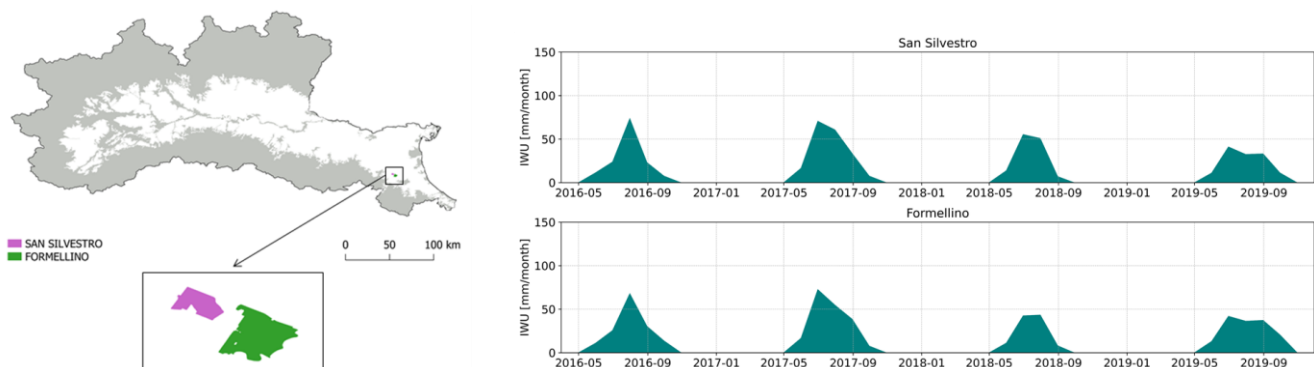


Figure 2.7: Location of the pilot districts in the Faenza area and time series of reference IWU over the San Silvestro and Formellino districts.

2.2.3 Umbria region, Italy

The Umbria region, located in central Italy, covers approximately 8,500 km² and is crossed by the River Tiber, whose upper-middle basin is characterized by predominantly hilly and mountainous terrain, with elevations ranging from 50 to 2,500 m a.s.l. Agricultural land represents about 49.3% of the region, while forests or semi-natural areas and urban areas account for 47.4% and 3.3%, respectively. The region has a Mediterranean climate, with an average annual precipitation of about 950 mm, mainly concentrated in autumn and winter, and a mean annual temperature of approximately 13 °C. The size and spatial extent of the irrigated fields and districts in the Umbria region are often not homogeneous, and have small extents due to complex orography.

Data sources for benchmark IWU over the Umbria region are regional authorities and water allocation managers (Agenzia Forestale Regionale Umbria, Consorzio di Bonificazione Umbra, and Consorzio di Bonifica Tevere Nera) and the data consist of seasonal district-aggregated irrigation volumes based on monitoring or estimation, covering the period 2015-2024.

The Agenzia Forestale Regionale Umbria controlled by the Umbria Region manages an extensive network of pipelines for irrigation water distribution, about 350 km of network, of the Alto Tevere district, about 148 km², divided into 5 irrigation subdistricts (Tevere I, Tevere II, Niccone, Carpina, and Lana). The main source of supply is the artificial lake of Montedoglio, located in the north of the Umbria region, which mainly serves the Tiber I subdistrict (approximately 77 km²). Other minor withdrawals are made from small reservoirs on secondary watercourses and directly from the Tiber River. In this district, the area actually irrigated mainly from June to August is around 20%, which is a common situation due to specific critical conditions of the agricultural sector in the Umbria region. The cultivated crops are corn and tobacco. Volume data were provided related to the period 2021-2024 but they need a further check and will be processed in a following stage of the analysis.

The Bonificazione Umbra Consortium manages an area of 61.4 km² divided into three districts (Marroggia, 16.3 km², Topino, 37 km², Clitunno, 8.1 km²). Approximately 75% of the Topino district is irrigated with flood irrigation systems, while the rest of the consortium's area is equipped with sprinkler systems. Irrigated fields are fed by withdrawals from the Topino and Clitunno rivers and from the artificial dam on the Marroggia stream. Topino district is cultivated from May to August, while Marroggia and Clitunno ones from May to September. The main cultivated crops in the consortium are vegetable crops, extensive herbaceous and cereal crops, tree crops and olive groves. Volumes withdrawn from different supply sources available in the period 2017-2024 for Topino district and 2015-2024 for Marroggia and Clitunno districts are shown in Figure 2.8. The Marroggia district is typically irrigated for 44-49% of the total equipped area, while the Topino and Clitunno districts for 40-43% and 21-22%, respectively in the monitoring period.

The Tevere-Nera Consortium manages an area of 38.9 km² irrigated by a network of two canals named Sersimone and Servino. About 20% of the district is irrigated by flood while the remaining part by sprinkler system. The irrigation period runs from May through September/October and the main crops are vegetables and cereals. About 20% of the district area is actually irrigated. Volumes withdrawn available in the period 2021-2024 range from 3.6 to 5.0 × 10⁶ m³ (Figure 2.8). The data are organised in a .csv file.

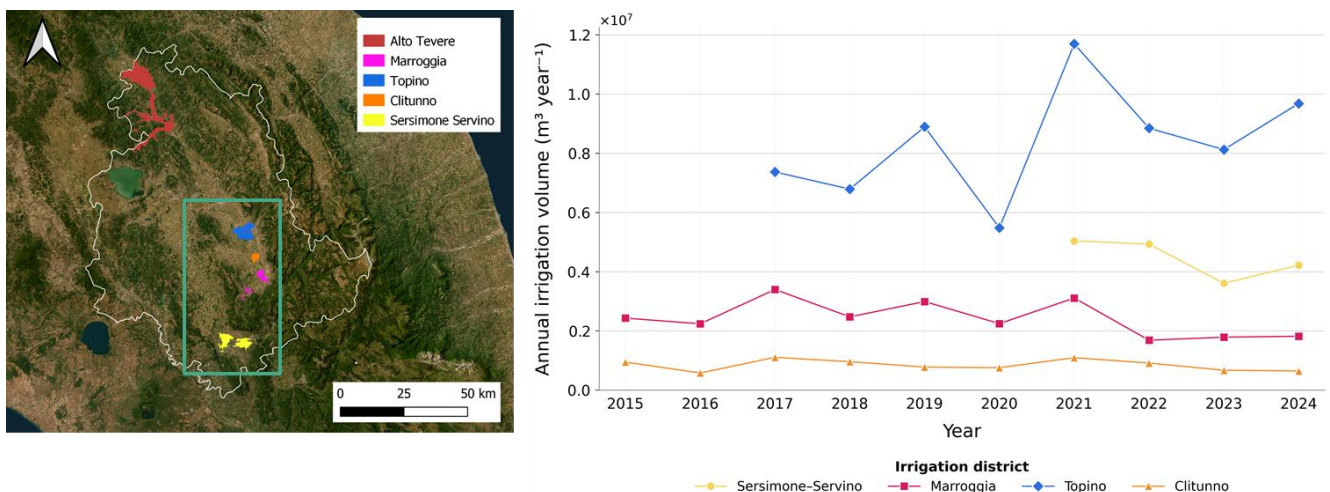


Figure 2.8: Districts belonging to the consortia of the Umbria region (central Italy) (in the green box the districts with data currently considered) and available time series of annual irrigation volume at district scale.

2.3 Murray-Darling basin (Australia)

The Murray–Darling Basin, whose river system extends for approximately 2530 km, is often regarded as Australia's food bowl. Covering more than 1.1 million km², or about 14% of the country's total area, the basin accounts for over two-thirds of Australia's irrigation water use. The region is frequently

affected by severe droughts, including the Millennium Drought of 2001–2009 (van Dijk et al., 2013) and, more recently, the 2017–2019 drought. Its predominantly arid and semi-arid climate is strongly influenced by large-scale climate variability. In particular, the El Niño phase of the El Niño–Southern Oscillation (ENSO) favours the occurrence of drought conditions across south-eastern Australia (Athukoralalage et al., 2024).

The Murray–Darling Basin is characterised by extensive plains, bordered to the east and south by the Great Dividing Range, which reaches an elevation of 2,228 m above sea level. Under natural conditions, the Murray River flows into the Southern Ocean through the Lower Lakes system and is fed by three major tributaries: the Goulburn–Broken River system, approximately 300 km long; the Darling River, approximately 2,750 km long; and the Murrumbidgee River, approximately 1,700 km long. Under natural flow conditions, these tributaries contribute approximately 17%, 14%, and 12% of the total inflow to the Murray River, respectively (Leblanc et al., 2012).

Approximately 42% of the available surface water is captured in farm dams or extracted from watercourses and is used primarily for irrigation (Leblanc et al., 2012). Irrigation is generally more extensive in the southern part of the basin, where it is supported by substantial water-storage infrastructure. Irrigated farms are often spatially fragmented and cultivate a wide variety of crops adapted to the markedly different environmental conditions found across the basin. Both surface water and groundwater are used throughout the catchment, with groundwater abstraction occurring mainly in the major alluvial aquifer systems.

Five irrigation districts in New South Wales were selected for the collection of benchmark irrigation data: Coleambally (977.0 km²), Murrumbidgee (2,789.3 km²), Western Murray (49.1 km²), Murray Mulwala (3092.6 km²), and Murray Wakool (1455.2 km²). The collected data is the same as phase 1 of the project. Figure 2.9 shows the location of the Murray–Darling Basin and the selected irrigation districts.

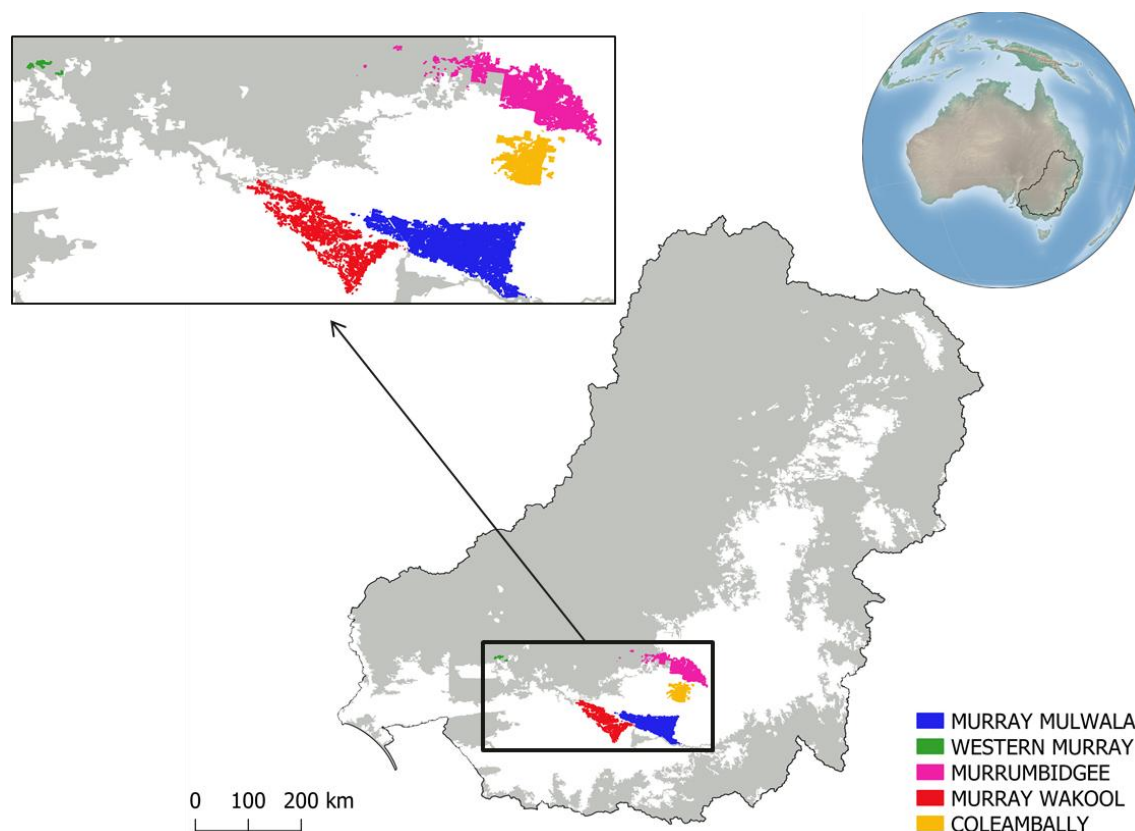


Figure 2.9: Murray-Darling basin: catchment boundaries and irrigated districts, including Murray Wakool, Murray Mulwala, Western Murray, Murrumbidgee and Coleambally.

Four of the five pilot districts cover an area close to or greater than 1,000 km². This represents an important feature for validation purposes, as the AWU estimates to be developed will mainly have a coarse spatial resolution of approximately 25 km. The districts are managed by irrigation infrastructure operators (IIOs), which are responsible for producing annual reports on irrigation water withdrawals (Bretreger et al., 2020). The Murray Mulwala and Murray Wakool districts are managed by the same IIO. Long-term monthly irrigation time series are available for all districts, with records beginning as early as 2003 in some areas. Information is also available on the temporal evolution of the proportion of each district's total area that was actually irrigated. Monthly irrigation amounts are expressed as equivalent water depth in mm month⁻¹ and were calculated by dividing the recorded irrigation volumes by the corresponding reference areas.

Further details on the individual districts and the associated datasets are provided below:

- Coleambally: The benchmark dataset covers the period from July 2009 to June 2019. Irrigation amounts were calculated by accounting for changes in the irrigated area during three periods: 2009–2013, using 2007 as the reference year; 2013–2017, using 2013 as the reference year; and 2017 onwards, using 2017 as the reference year.
- Murray Mulwala: The dataset covers the period from July 2010 to June 2019. As for Coleambally, irrigation amounts were calculated by considering changes in the irrigated area during 2010–2013, with 2007 as the reference year; 2013–2017, with 2013 as the reference year; and 2017 onwards, with 2017 as the reference year.
- Murray Wakool: The dataset covers the period from July 2010 to June 2019. Irrigation amounts were calculated by accounting for the evolution of the irrigated area during 2010–2013, using 2007 as the reference year; 2013–2017, using 2013 as the reference year; and 2017 onwards, using 2017 as the reference year.
- Murrumbidgee: The dataset covers the period from July 2013 to June 2019. Irrigation amounts were calculated by considering changes in the irrigated area during 2013–2017, using 2013 as the reference year, and from 2017 onwards, using 2017 as the reference year.
- Western Murray: The dataset covers the period from July 2003 to June 2019. Irrigation amounts were calculated by accounting for changes in the irrigated area during 2003–2013, using 2007 as the reference year; 2013–2017, using 2013 as the reference year; and 2017 onwards, using 2017 as the reference year.

Figure 2.10 provides an overview on the collected data. The data are stored into a .nc file.

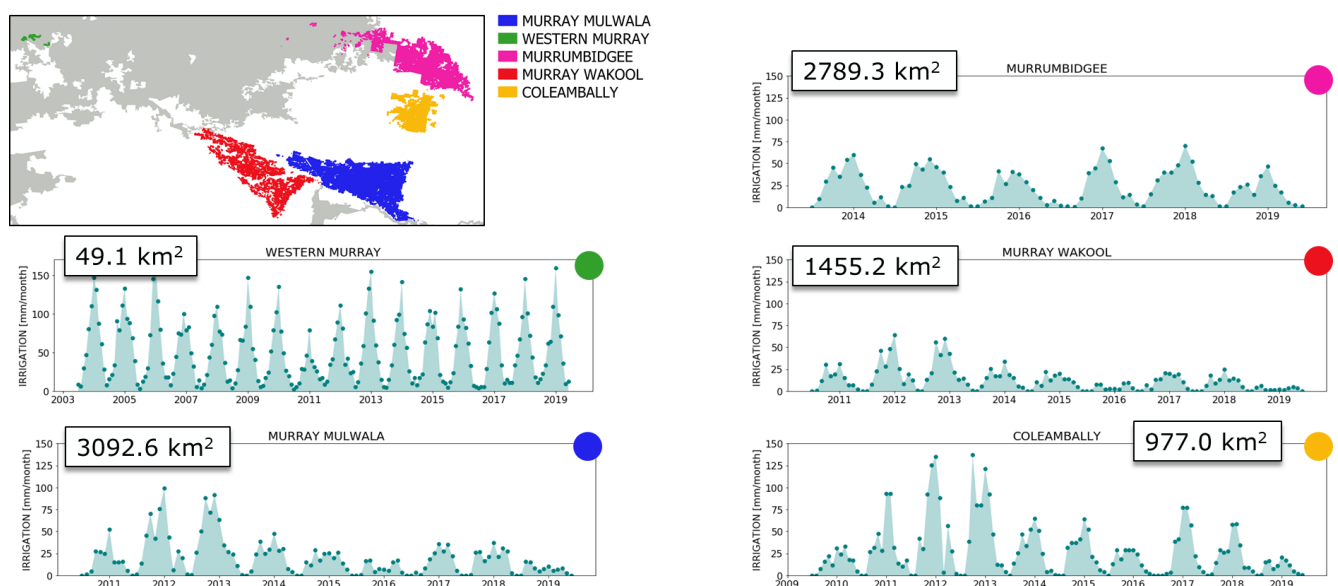


Figure 2.10: Time series of reference IWU available for five pilot districts in the Murray-Darling basin, Australia.

3. Reference grid and study areas boundaries

For the CCI-AWU IMPRES project purposes the consortium decided to run all the experiments over a common grid based on the ESA CCI Surface Soil Moisture COMBINED active+passive medium resolution product (see Section 4.1) v08.1 at a 0.1° spatial resolution.

Specific boxes were defined in order to allow a better comparison of the project's results in terms of long-term datasets of irrigation. Table 1 shows the boxes' limits.

Table 3.1: Limits of the boxes defined for each of the project's pilot areas.

Study Area	Lower left lat (°)	Lower left lon (°)	Upper right lat (°)	Upper right lon (°)
CONUS	24.875	-124.875	49.375	-66.875
Europe	35.000	-11.000	72.000	50.000
Murray-Darling	-37.875	138.375	-24.375	152.625

4. Satellite observations and meteorological data

4.1 ESA CCI soil moisture medium resolution

The ESA CCI SM Medium Resolution (MR) version 9.2 product is a new, improved-resolution version of the long-standing ESA CCI Soil Moisture product (Dorigo et al., 2017; Gruber et al., 2019), developed by TU Wien and EODC within ESA's CCI programme. As with the standard CCI SM product used in the first phase of the CCI-AWU project, it combines soil moisture observations from several active (ASCAT-A/B/C, via the H-SAF H121 product) and passive (AMSR-E, AMSR2, SMOS, SMAP, GMI, FengYun-B/C/D) sensors into a single COMBINED product. The production chain follows the same methodology as the main product: passive observations are first resampled onto the target grid using a nearest-neighbour approach (k-d tree search, 17.5 km radius; reprojection via GDAL for SMOS and SMAP, which are provided on the EASEv2 grid), soil moisture is retrieved from brightness temperatures using the LPRM model for passive sensors and a change-detection algorithm for the active data, and the individual sensor time series are harmonised with one another through Cumulative Distribution Function (CDF) matching (applied per grid point) before being merged via a weighted average based on the sensor uncertainties estimated through Triple Collocation Analysis (TCA).

The main difference from the standard CCI SM product lies in the spatial resolution, increased from 0.25° to 0.1° (a global 3600 × 1800 grid). This finer resolution, close to the native resolution of several contributing sensors (AMSR-E/2, ASCAT, SMAP, GMI), allows a better characterisation of soil moisture contrasts at local scale, typically irrigated scenes, which are often too small to be resolved at 0.25°. The product delivers COMBINED surface soil moisture (SSM, roughly 0 to 5 cm) at a daily time step, covering the period from 2002 to 2024, and has been available since summer 2025.

The ESA CCI SM MR data were retrieved and prepared for the project's three study areas (Europe, CONUS and the Murray-Darling Basin) to build a daily data record, resampled over the selected analysis domains and ready to be used as the primary input for the SM-based Delta and SM-based Inversion methods. It was also downscaled to 1 km using the DISPATCH algorithm. Figure 4.1 shows the prepared data, with mean soil moisture maps, with their uncertainties, for each of the three regions.

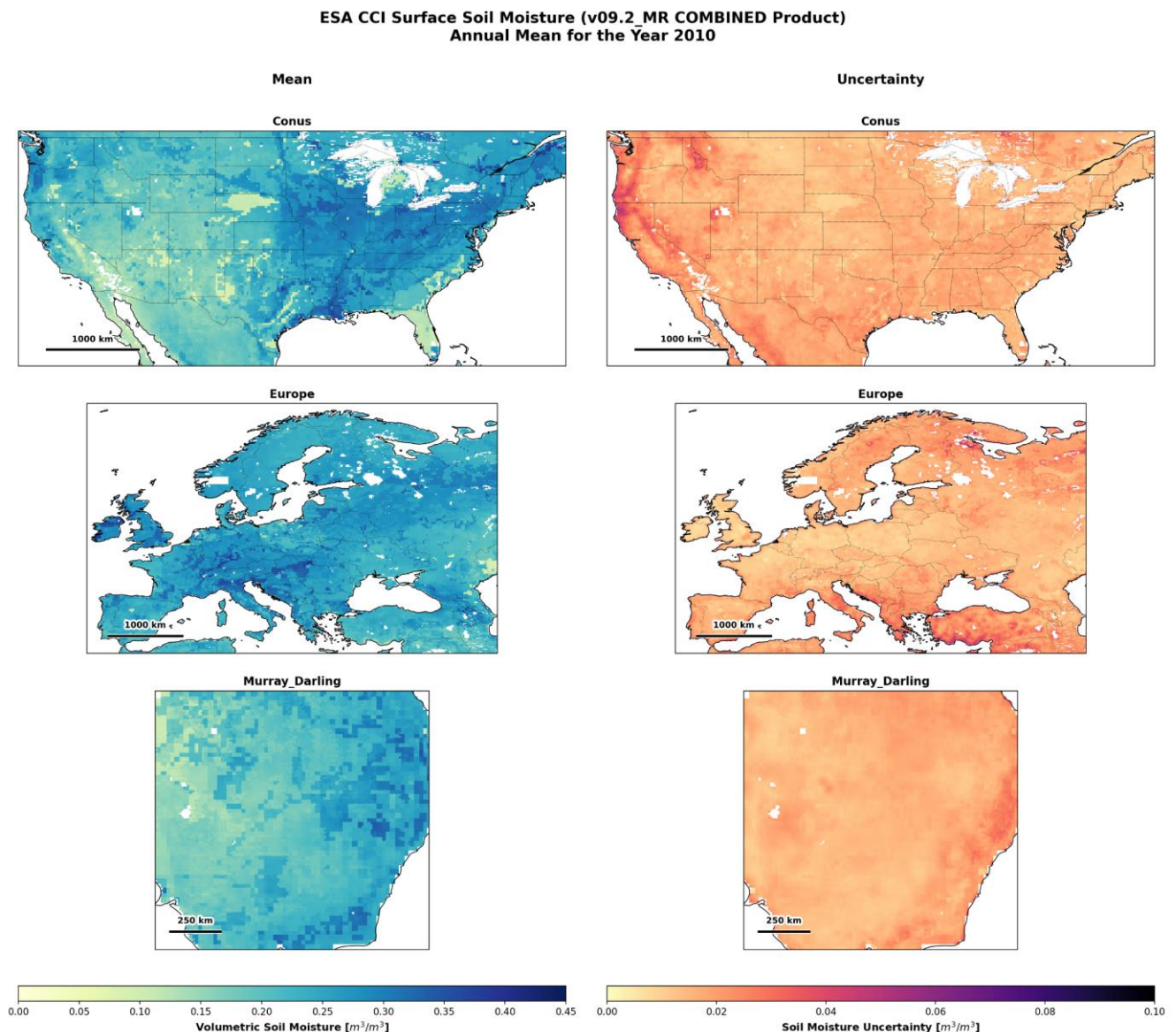


Figure 4.1: ESA CCI SM (mean and uncertainty) product over the three different study areas at 0.1° resolution

4.2 DISPATCH downscaled soil moisture

Three DISPATCH (DISaggregation based on Physical And Theoretical scale Change) downscaled soil moisture (SM) products were developed at 1 km spatial resolution and a daily time step. They were obtained by combining MODIS observations of Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) with the coarse-resolution SM products of SMOS (Kerr et al., 2010), SMAP (Entekhabi et al., 2010) and ESA CCI COMBINED SM Medium Resolution (Dorigo et al., 2017; Gruber et al., 2019). An overview of the products and their specifications is provided in Table 4.1.

Table 4.1: Overview of the input datasets used to produce the DISPATCH downscaled soil moisture products.

Source	Product (version)	Variable	Native spatial res.	Native temporal res.	Temporal coverage
SMOS	MIR_SMUDP2 (v700)	Soil moisture	~40 km	Daily	2010–2025
SMAP	SPL3SMP_E (v006)	Soil moisture	9 km	Daily	2015–2025
ESA CCI	SM MR (v9.2)	Soil moisture	0.1° (~11 km)	Daily	2002–2024
MODIS Aqua/Terra	MYD11A1 / MOD11A1 (v061)	LST	1 km	Daily	2000–present
MODIS Terra	MOD13A2 (v061)	NDVI	1 km	16-day	2000–present

The products shown in Table 4.1 were downloaded and prepared to be processed within the DISPATCH pipeline. The disaggregation algorithm distributes high-resolution soil moisture around the observed coarse-resolution mean value by using the relation between optical-derived soil evaporative efficiency and soil moisture (Molero et al., 2016; Escorihuela and Quintana-Seguí, 2016). The original coarse-resolution SM is disaggregated to the 1 km pixel grid of MODIS, using MODIS' LST, NDVI and fractional vegetation cover observations to derive the soil evaporative efficiency at each high-resolution pixel. The coarse-resolution SM is then downscaled to the 1 km grid through a linear model that links the top layer of soil moisture (i.e., the first 5 cm of depth) with the soil evaporative efficiency.

DISPATCH is described in detail in Merlin et al. (2012, 2013) and Molero et al. (2016). The linear implementation used in this project, including the extension for vegetation cover (Ojha et al., 2021), is described in Sánchez Alcalde and Escorihuela (2025). The main equations are summarised below. The downscaling relationship distributes the low-resolution (LR) SM around its observed value according to the deviation of the high-resolution (HR) soil evaporative efficiency (SEE) from its LR aggregate:

$$SM_{HR} = SM_{LR} + \left(\frac{\partial SM_{mod}}{\partial SEE} \right)_{SEE_{HR}=SEE_{LR}} \times (SEE_{HR} - SEE_{LR})$$

where SM_{HR} is the disaggregated SM at 1 km, SM_{LR} is the SM observed by the coarse-resolution product (SMOS, SMAP or ESA CCI), SM_{mod} is the model relating SM to SEE, SEE_{HR} is the SEE derived from MODIS at 1 km, SEE_{LR} is the aggregation of SEE_{HR} within the LR pixel, and $\partial SM_{mod} / \partial SEE$ is the partial derivative of SM with respect to SEE evaluated at SEE_{LR} . The SEE at HR is estimated from the soil surface temperature:

$$SEE_{HR} = \frac{T_{s,max} - T_{s,HR}}{T_{s,max} - T_{s,min}}$$

where $T_{s,HR}$ is the soil surface temperature at 1 km, and $T_{s,max}$ and $T_{s,min}$ are the soil temperatures in fully dry ($SEE = 0$) and water-saturated ($SEE = 1$) conditions, respectively. These temperature end-members are estimated from the maximum and minimum values of the observed LST within the LST– f_{vg} feature space obtained with MODIS data. The soil temperature is obtained from the linear decomposition of LST into soil and vegetation temperatures using the trapezoid method (Merlin et al., 2012):

$$T_{s,HR} = \frac{LST_{HR} - f_{vg,HR} \times T_{v,HR}}{1 - f_{vg,HR}}$$

where LST_{HR} is the MODIS LST at 1 km, $f_{vg,HR}$ is the fractional vegetation cover derived from MODIS NDVI, and $T_{v,HR}$ is the vegetation temperature, bounded by its minimum ($T_{v,min}$) and maximum ($T_{v,max}$) values. The DISPATCH 1 km SM has been validated against in situ measurements under different

climatic conditions, including Catalonia (Merlin et al., 2013), south-eastern Australia (Merlin et al., 2012) and Morocco (Stefan et al., 2020).

The three 1 km SM datasets have been produced over the six irrigation-intensive sub-regions (California Central Valley, Snake River Plain, Mississippi Floodplain and Great Plains in the CONUS, and the Po Valley and the Ebro Basin in Europe), covering the period 2002-2024, 2010-2025, and 2015-2025 for the ESA CCI-, SMOS-, and SMAP-based products, respectively. These 1 km soil moisture datasets provide the high-resolution input for the 1 km IWU estimate experiments to be carried out over these sub-regions, feeding the SM-based Delta and SM-based Inversion methods; the former additionally uses the 1 km actual evapotranspiration products described in Section 4.3.

The pipeline to acquire the final 1 km SM datasets consisted of the following steps:

- Download the products listed in Table 4.1 and, when applicable, mask the raw files to remove low-quality pixels due to clouds, radio-frequency interference (RFI; SMOS pixels with RFI values above 0.2 are excluded) or other sources of noise;
- Clip the data with worldwide coverage to the MODIS tiles that overlap over the areas of interest;
- Run the DISPATCH algorithm with the different input configurations over all relevant MODIS tiles to obtain daily SM at 1 km;
- Crop and merge different SM tiles according to the desired shapefile.

The downscaled SM 1 km datasets have been uploaded as daily NetCDF files to the shared folder of the project, following the naming convention 'SM1km_AOI_date_PX1.nc', where AOI is the name of the area of interest, date is the corresponding day in the format YYYYMMDD, and PX1 indicates the satellites that have been used, being X=1 for SMOS, X=2 for SMAP, and X=3 for ESA CCI.

Figure 4.2 shows the ESA CCI SM 1 km product over the six study areas and Figure 4.3 shows the three SM images produced for the same day at the Ebro basin. The latter illustrates the differences between the three datasets.

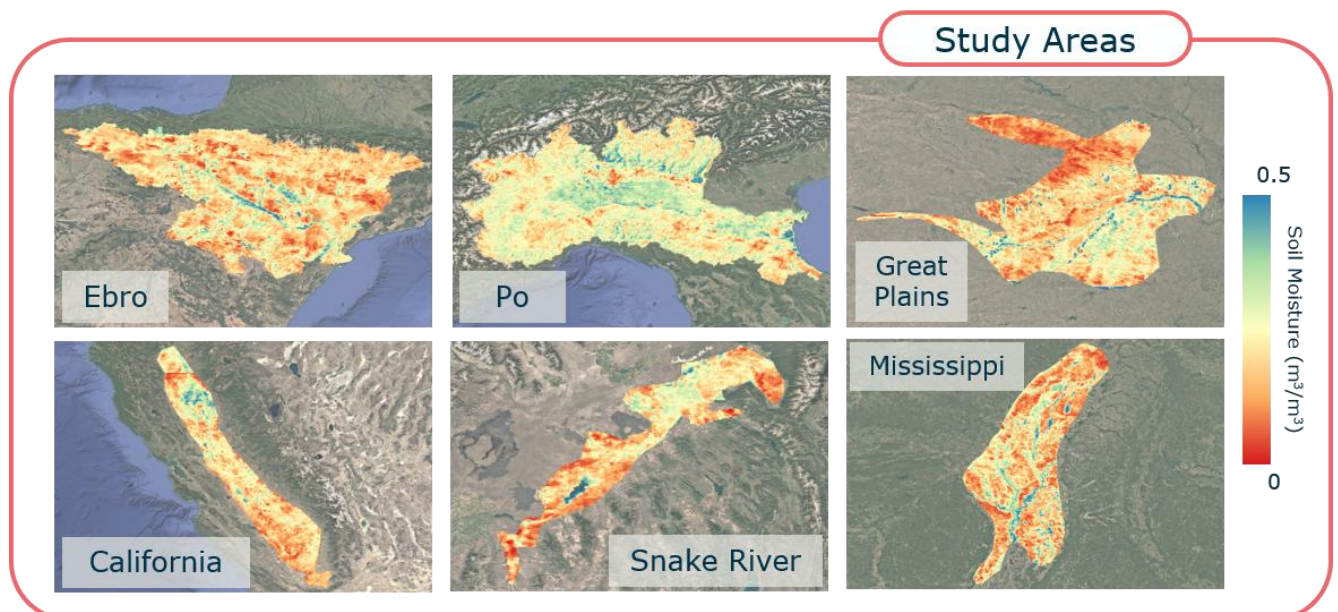


Figure 4.2: SM at 1 km derived using ESA CCI COMBINED MR over the different areas of study.

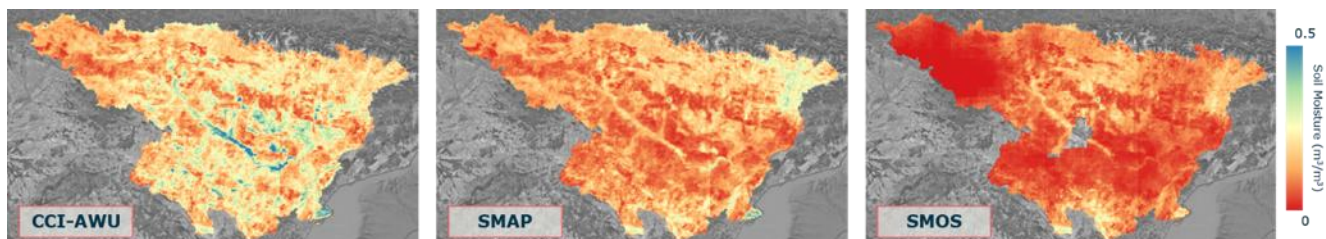


Figure 4.3: SM maps of the Ebro basin for the 23rd of August 2024 using the CCI, SMAP, and SMOS configuration.

Due to the difference between the datasets, as shown in Figure 4.3, an inter-comparison test was carried out across the different regions during the shared period 2016-2024.

A temporal and spatial coverage analysis showed that the SM derived from ESA CCI COMBINED MR had the most complete availability in both aspects, with few and scattered missing days for some regions. The SM data derived using SMAP tends to have more missing days owing to its 1–3 day revisit time, depending on the region. Finally, the SMOS-derived SM has the most spatial gaps for almost every region of study. Figure 4.4 is an example of the temporal coverage of each dataset over the Po basin for the period 2016-2024, where the solid colour bars indicate days with a spatial coverage over 60% of valid pixels. In addition to confirming the behaviour described above, this figure also reveals a concern regarding the SMOS SM dataset that affects the Po basin and, to a lesser extent, the Ebro basin. Since 2022, the RFI in L-band has intensified over central-eastern Europe, linked to emissions associated with geopolitical conflicts. Consequently, an increasing fraction of SMOS retrievals exceeds the RFI threshold applied during pre-processing (0.2) and is discarded, resulting in more spatial and temporal gaps in this dataset.

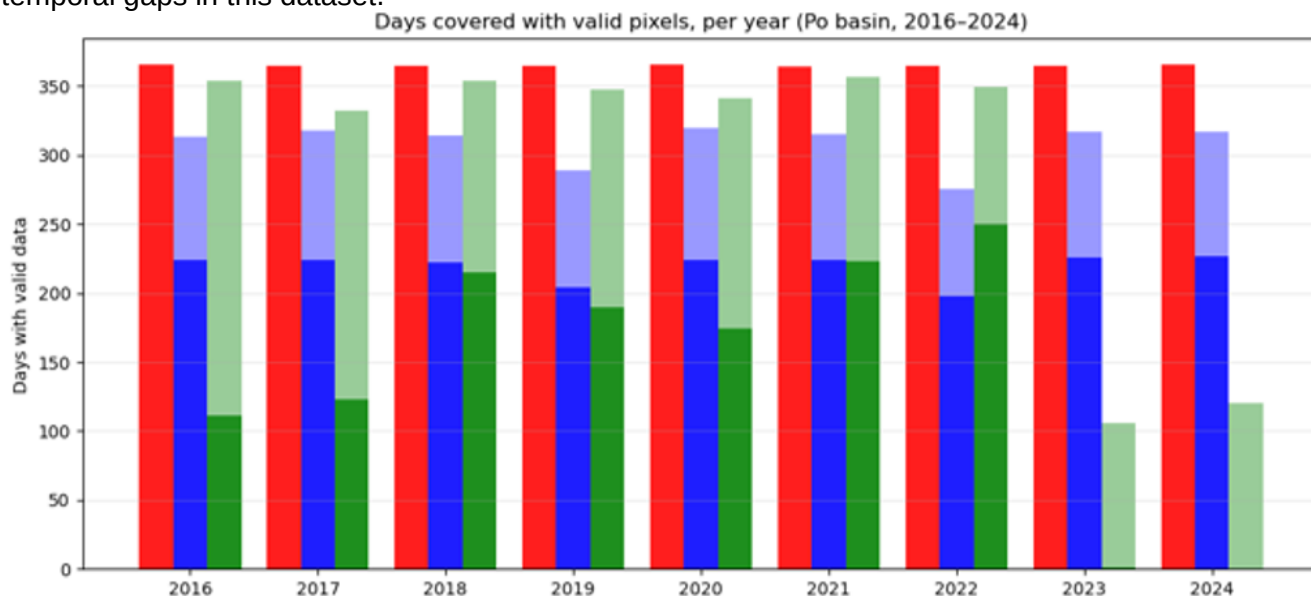


Figure 4.4: Temporal coverage of the different 1 km SM datasets (CCI in red, SMAP in blue, and SMOS in green) over the Po basin for the period 2016-2024. The solid colour bars indicate days with spatial coverage over 60% of valid pixels.

The seasonal climatology of each region was also studied by spatially averaging the SM values and then computing the monthly-averaged SM over the period 2016-2024. Figure 4.5 shows the behaviour across the different sites: the CCI SM downscaled dataset tends to exhibit the wettest values and SMOS the driest. Furthermore, the 1 km SM dataset derived from ESA CCI data has the tightest standard deviations, suggesting that the blending of different satellite data used to create the ESA CCI COMBINED MR data may smooth the heterogeneity of the landscapes. On the other hand, the 1 km

SM dataset derived from SMOS has the highest standard deviation values, which may indicate that it captures more fine spatial details compared to the other datasets.

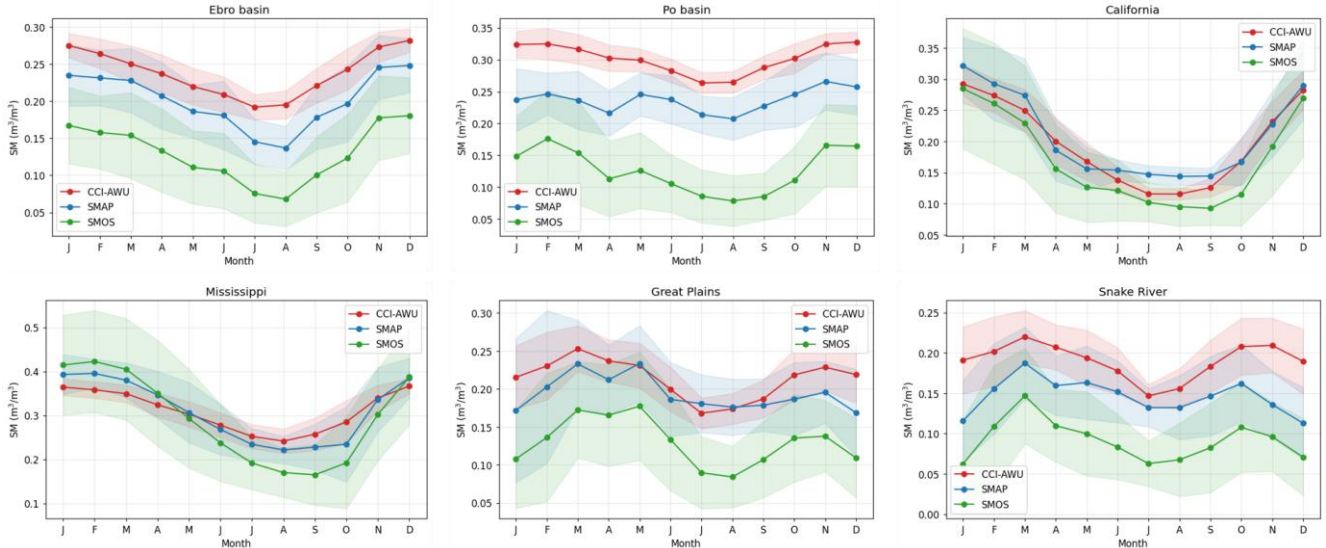


Figure 4.5: Seasonal climatology of each area of study. The shaded bands correspond to the spatially and monthly averaged standard deviation.

Finally, Table 4.2 shows the inter-comparison metrics between the datasets. In general terms, the Ebro basin, California and Mississippi are the regions with the strongest correlation agreement between the datasets, while the other three areas have lower correlation values. The bias again confirms that the CCI-derived dataset tends to be the wettest and the SMOS-derived the driest.

These metrics are not intended as an accuracy assessment, but as a characterisation of the consistency between the three 1 km products. They will be used to interpret the differences between the 1 km IWU estimates obtained with each SM input in the SM-based Delta and SM-based Inversion experiments: regions with strong agreement are expected to yield consistent IWU estimates regardless of the input, whereas lower correlations or larger biases (e.g., over the Po, the Great Plains and the Snake River) indicate where the choice of SM input is likely to have a greater impact on the IWU retrieval. It should also be noted that the three datasets are not independent. The ESA CCI COMBINED MR product merges, among others, SMOS and SMAP retrievals (Section 4.1), and all three products share the same MODIS LST and NDVI inputs and the same DISPATCH downscaling, so their 1 km spatial patterns are partly imposed by the common SEE fields. Consequently, the correlations in Table 4.2 are likely to be higher than those that would be obtained between fully independent products, and the metrics cannot be interpreted as error estimates of any individual dataset.

Table 4.2: Inter-comparison metrics between the three DISPATCH downscaled SM datasets. Colour key for correlation: green, yellow, and red present strong, acceptable, and weak correlations, respectively. Colour key for bias: blue and red stand for positive and negative bias, respectively.

Area	CCI-AWU vs SMAP		CCI-AWU vs SMOS		SMOS vs SMAP	
	R	bias	R	bias	R	bias
Ebro	0.887	+0.035	0.816	+0.107	0.805	-0.071
Po	0.686	+0.061	0.686	+0.175	0.601	-0.116
California	0.936	-0.010	0.840	+0.026	0.889	-0.033
Mississippi	0.932	-0.002	0.837	+0.015	0.882	-0.014
Great Plains	0.586	+0.017	0.730	+0.080	0.719	-0.061
Snake River	0.683	+0.041	0.765	+0.094	0.801	-0.054

To conclude the analysis of the DISPATCH downscaled SM generated at 1 km, two further limitations of the datasets are worth noting. First, SMAP experienced a data outage from 19 June to 23 July 2019; in addition, from 8 August to 16 October 2022 it entered a protected safe mode, halting its science data acquisition. Hence, the SM product derived from SMAP presents operational gaps during these two periods for all the areas of study.

The other issue concerns the coverage limitation caused by snow and ice in all three datasets produced. During the coldest months, the number of measurements for the Snake River and the Great Plains areas is reduced substantially due to the presence of snow and ice. Figure 4.6 shows the temporal and spatial coverage separated by months over the Snake River, demonstrating the increase in data gaps caused by snow and ice cover.

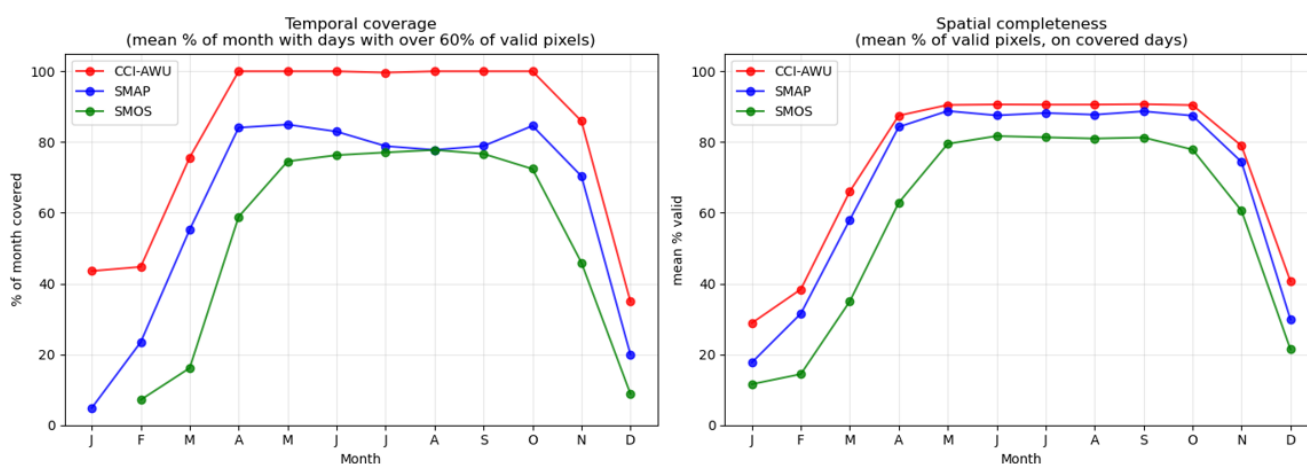


Figure 4.6: Temporal and spatial coverage for the spatially and monthly averaged SM 1 km data over the Snake River area over the period 2016-2024.

All the three DISPATCH downscaled data sets will be tested as input to algorithms implemented in WP300 to develop IWU estimates. Validation against reference irrigation volumes will help in assessing best performing products across the different pilot areas.

4.3 Evapotranspiration

Two families of evapotranspiration (ET) products were prepared: potential ET (PET), which provides the atmospheric water demand, and actual ET (ETa). An overview of the products, their native characteristics and how they were prepared for the project is given in Table 4.3.

GLEAM4.3a Potential Evapotranspiration

Potential ET was taken from GLEAM4.3a (Miralles et al., 2025), a hybrid model combining physically based process representations with machine-learning parameterizations. In GLEAM, potential evaporation (Ep) is computed with the Penman equation from net radiation, near-surface air temperature, wind speed, vegetation height, and vapour pressure deficit. GLEAM4.3a is provided at 0.1° spatial resolution and daily time step, covering the period 2000 to 2025, and was prepared at that resolution over the three study areas (Europe, CONUS and the Murray-Darling Basin), on the same grid as the ESA CCI SM MR data. This dataset feeds the SM-based Inversion method.

Actual Evapotranspiration (SSEBop v6.1, PMLv2, MOD16A2GF)

Three satellite-based actual ET (ETa) products were prepared to feed the ETa term of the SM-Delta method. Using three independent products rather than one also allows the spread between ET estimates to be assessed in the IWU retrieval.

Table 4.3. Overview of the evapotranspiration products prepared in the project.

Product	Type	Model	Original spatial res.	Original temporal res.	Temporal coverage	Processed res.
GLEAM4.3a	PET	Hybrid (Penman + ML)	0.1°	Daily	2000-2025	0.1°
SSEBop v6.1	ETa	Simplified surface energy balance	1 km	Monthly	2012-2024	0.1° + 1 km
PML (v2.2a)	ETa	Semi-mechanistic Penman-Monteith	500 m	8-day	2002-2024	0.1° + 1 km
MOD16A2GF (v061)	ETa	Modified Penman-Monteith	500 m	8-day	2000-2025	0.1° + 1 km

SSEBop v6.1. SSEBop v6.1 (Senay et al., 2023) is based on a simplified surface energy balance. ET is computed as the product of a reference evapotranspiration (ET₀), taken from the climatological Penman-Monteith fields of TerraClimate, and an evaporative fraction (ET_f) derived from VIIRS land surface temperature (LST; Hulley et al., 2018). ET_f compares each pixel's LST to a dynamically estimated "cold/wet" reference temperature representing maximum ET conditions, computed locally within a 5 × 5 km moving window from NDVI-LST relationships to identify well-watered vegetation (FANO algorithm; Senay et al., 2023). The product is provided at 1 km spatial resolution and monthly temporal resolution, covering the period 2012 to 2024.

PMLv2. PMLv2 (Zhang et al., 2019) is a semi-mechanistic model based on a modified Penman-Monteith equation. Vegetation water stress is handled through the VPD, derived from GLDAS-2.1, which regulates both stomatal conductance and surface resistance. The VPD response is calibrated separately for each biome against 95 flux towers, including 11 in the cropland biome (four of them irrigated). Inputs include MODIS-derived variables (LAI, albedo, emissivity) and daily GLDAS-2.1 meteorological forcings (precipitation, air temperature, humidity, radiation, wind speed). The product is provided at 500 m spatial resolution and 8-day temporal resolution, covering the period 2002 to 2024.

MOD16A2GF. MOD16A2GF V061 (Running et al., 2021) uses an algorithm based on the Penman-Monteith equation that combines MODIS surface and vegetation properties (LAI, fAPAR, albedo, and land cover) with daily meteorological reanalysis inputs. Water stress is represented through the surface resistance term (rs), which combines stomatal regulation based on VPD and minimum air temperature (T_{min}) with canopy scaling from MODIS LAI and fAPAR. As an improved, year-end gap-filled dataset,

it cleans poor-quality inputs from 8-day LAI and fAPAR using linear interpolation. The product is provided at 500 m spatial resolution and 8-day temporal resolution, covering the period from 2000 to 2025.

The three ETa products were prepared at 0.1° over the three study areas (Europe, CONUS and the Murray-Darling Basin), on the same grid as the ESA CCI SM MR data. They were additionally prepared at 1 km over the six irrigation-intensive sub-regions (the California Central Valley, the Snake River Plain, the Mississippi Floodplain and the Great Plains in the CONUS, and the Po Valley and the Ebro Basin in Europe), where they were resampled using an area-weighted method onto the grid of the DISPATCH-downscaled SM products. Figure 4.7 shows mean ET maps for the prepared datasets across the selected study area of Europe (0.1°). Figure 4.8 shows mean ET maps for the prepared datasets for the Ebro region at 1km spatial resolution.

Comparison of 0.1° ET Products over Europe Full Period Mean

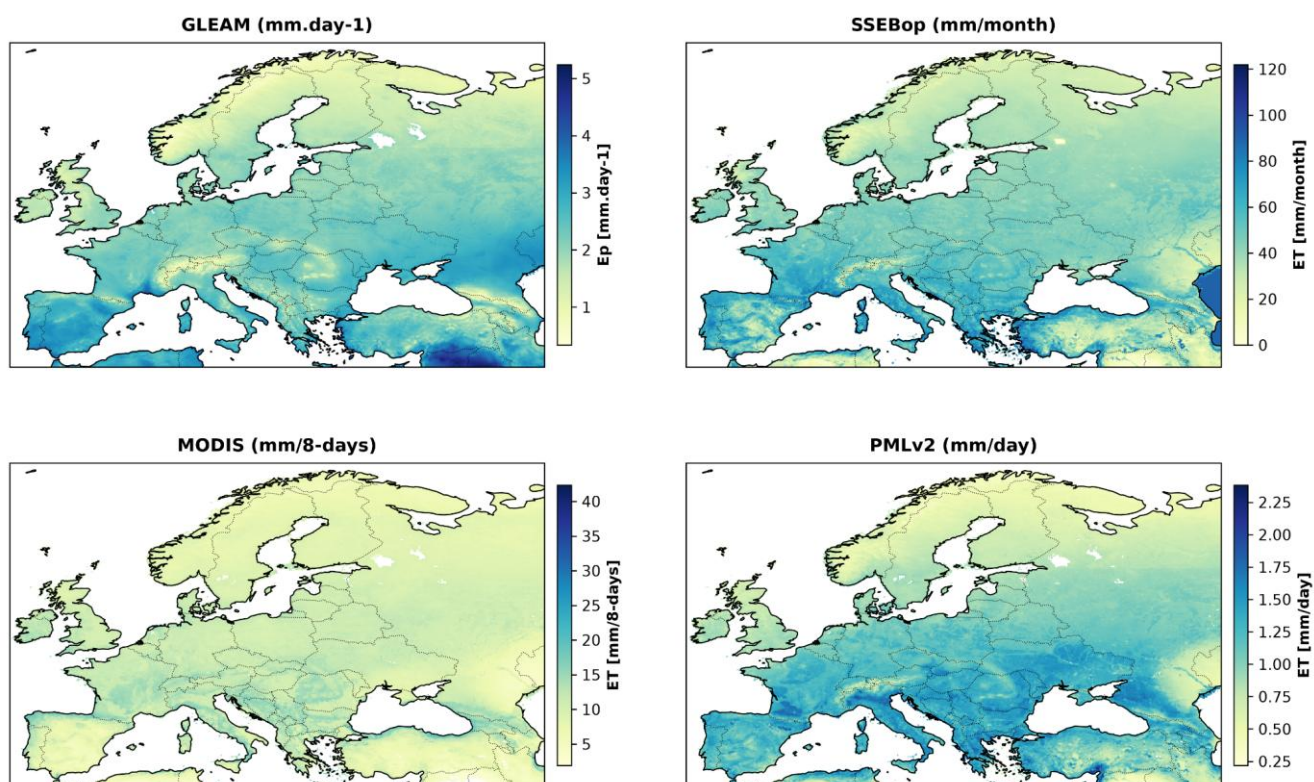


Figure 4.7: Different evapotranspiration products compared over the study area Europe (0.1° resolution)

Comparison of 1km ET (Mean) Products over Ebro Basin

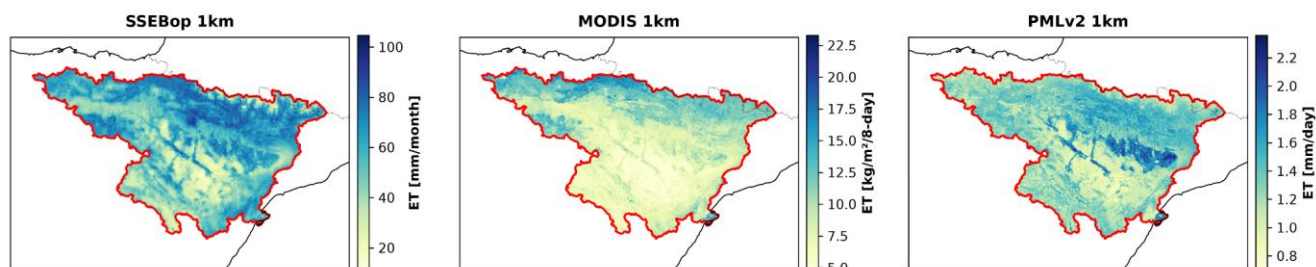


Figure 4.8: Different ET products compared in Ebro at 1km spatial resolution

4.4 Meteorological data

Precipitation forcing was taken from AgERA5 (Agrometeorological indicators from 1979 to present derived from reanalysis) (Boogaard et al., 2020), a daily agrometeorological dataset derived from the ECMWF ERA5 reanalysis. AgERA5 is provided at a native spatial resolution of 0.1° and daily time step, covering the period from 1979 to present. The precipitation unit is [mm/day].

AgERA5 precipitation was processed within the Land Information System Framework (LISF) (Kumar et al., 2006), where the run domains were defined directly in the Land Data Toolkit (LDT) configuration. Three separate run domains were set up to match the same grid as the ESA CCI SM MR data, each domain corresponding to the project's study areas: CONUS, Europe and the Murray-Darling Basin. Each domain was run independently within LISF, with buffered extents to avoid edge effects from bilinear resampling, before being cropped post-run to the corresponding bounding box of each study area.

The resulting AgERA5 precipitation records were prepared as NetCDF files over the three study areas (Europe, CONUS and the Murray-Darling Basin), on the same grid as the ESA CCI SM MR and evapotranspiration datasets, ready for use as forcing input to the IWU retrieval methods. Each NetCDF file holds all daily data from 01/01/1990 to 01/01/2026. Additionally, the focus region of the Ebro was clipped out of the resulting Europe grid and presented as a fourth separate precipitation grid. An example of the precipitation data is shown in Figure 4.9 for each study area.

AgERA5 Precipitation on 31-07-2022

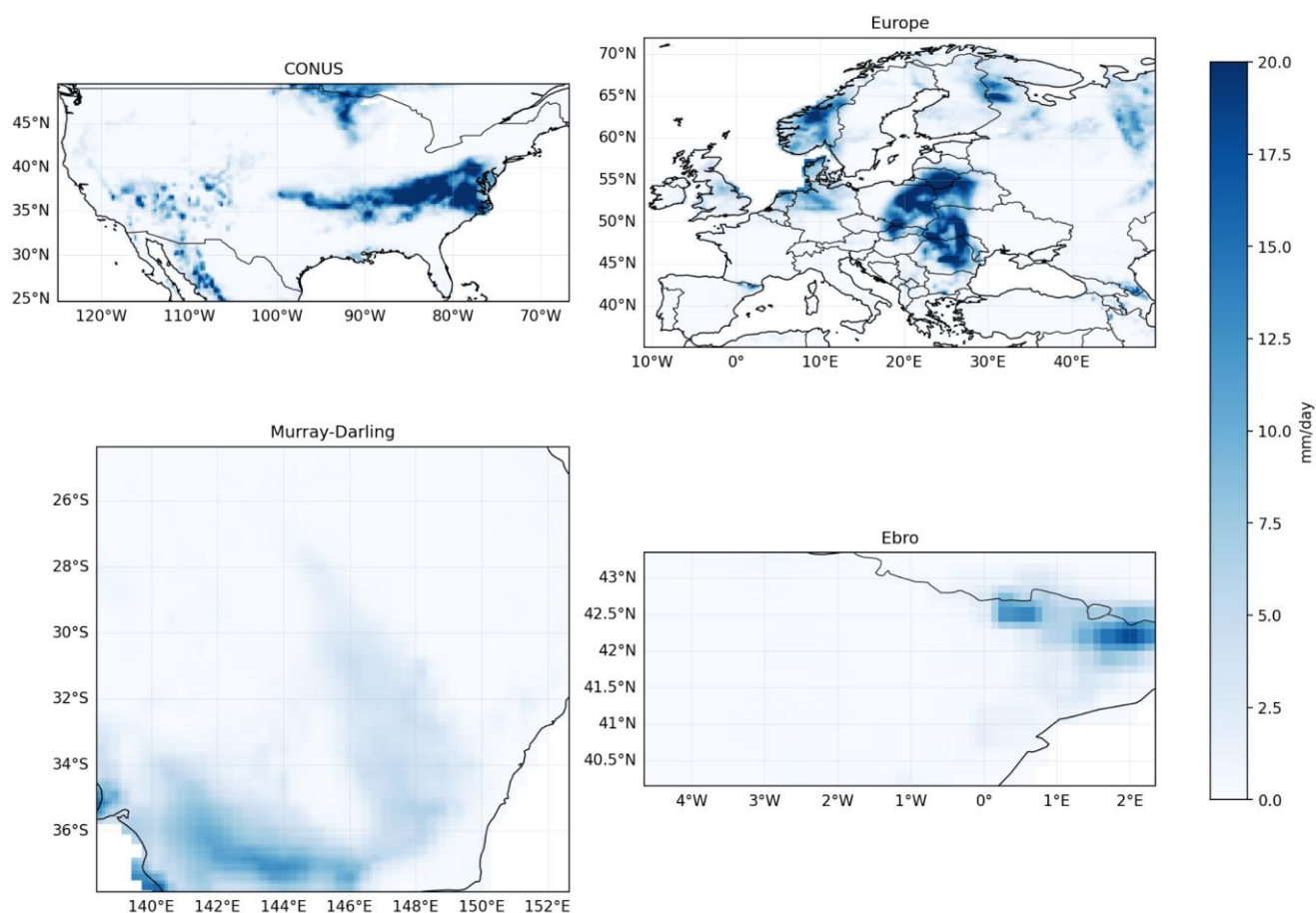


Figure 4.9: Precipitation from the AgERA5 forcing dataset on 31/07/2022 for each study area.

Besides the precipitation data that is shared with the project partners, additional AgERA5 data will be used later on in the project by the KU Leuven research group. The variables minimum and maximum temperature and FAO-Penman-Monteith reference evapotranspiration will be used for irrigated crop simulations with the LISF-AquaCrop model. This data was also prepared and is ready to use for WP330.

5. Summary

Tables 4.4 and 4.5 summarise satellite and auxiliary/ancillary input data involved in this report.

Table 4.4. Input satellite data.

Sensor / Instrument	Level	Version	Temporal Coverage	Spatial Coverage	Provider	Access Link	Used for	Notes
SMOS / MIRAS (L-band radiometer)	L2	MIR_SMUD P2 (v700)	2010-2025	Global, ~40 km	ESA	smos-diss.eo.esa.int	Coarse-resolution SM input to DISPATCH	Pixels with RFI>0.2 excluded; Increasing RFI over central-eastern Europe since 2022.
SMAP / L-band radiometer	L3	SPL3SMP-E (v006)	2015-2025	Global, 9 km (EASE-Grid 2.0)	NASA NSIDC DAAC	https://nsidc.org/data/sp13smp_e/versions/6	Coarse-resolution SM input to DISPATCH	Data gaps 19 Jun - 23 Jul 2019 (outage) and 8 Aug - 16 Oct 2022 (safe mode)
ESA CCI SM COMBINED MR	L3	v9.2	2002-2024	Global, 0.1°	ESA CCI (TU Wien / EODC)	https://researchdata.tuwien.ac.at/records/k32ss-1kh79	Coarse-resolution SM input to DISPATCH + Input SM dataset for IWU estimates	—
MODIS Terra / Aqua - LST	L3	MOD11A1 MYD11A1 (v061)	2000-2025	Global, 1 km	NASA LP DAAC	https://www.earthdata.nasa.gov/data/catalog/lpcloud-mod11a1-061	Soil temperature and soil evaporative efficiency in DISPATCH	—
MODIS Terra - NDVI	L3	MOD13A2 (v061)	2000-2025	Global, 1 km	NASA LP DAAC	https://www.earthdata.nasa.gov/data/catalog/lpcloud-mod13a2-061	Fractional vegetation cover in DISPATCH	—
GLEAM (hybrid Penman + ML model)	L4	GLEAM4.3a	2000-2025	Global, 0.1°	GLEAM	https://www.gleam.eu	Potential ET (Ep) input to SM-based Inversion	Daily. Prepared at 0.1° on the ESA CCI SM MR grid

SSEBop	L4	v6.1	2012-2024	Global, 1 km	USGS	https://earthwarning.usgs.gov/ssebop	ETa term of SM-Delta	Monthly. Prepared at 0.1° and 1 km
PML	L4	PMLv2 (v2.2a)	2002-2024	Global, 500 m	Zhang et al. (2019)	https://developers.google.com/earth-engine/datasets/catalog/projects_pml_evapotranspiration_PML_OUTPUT_PML_V22a	ETa term of SM-Delta	8-day. Prepared at 0.1° and 1 km
MODIS Terra + Aqua	L4	MOD16A2GF (v061)	2000-2025	Global, 500 m	NASA LP DAAC	https://www.earthdata.nasa.gov/data/catalog/lpcLOUD-mod16a2gf-061	ETa term of SM-Delta	8-day, year-end gap-filled. Prepared at 0.1° and 1 km

Table 4.5. Input auxiliary/ancillary data.

Dataset / Field	Type	Version	Temporal Coverage	Spatial Resolution	Provider	Access Link	Used for	Notes
AgERA5	Gridded, reanalysis	2.0	Daily	0.1° x 0.1°	Copernicus Climate Change Service (C3S)	Agrometeorological indicators from 1979 to present derived from reanalysis	Precipitation data, later on also for crop simulations	-
GMIA (Global Map of Irrigation Areas)	Gridded, static map	5.0	Static (reference year ~2005)	5 arcmin (~9 km)	FAO	https://www.fao.org/aquastat/en/geospatial-information/global-maps-irrigated-areas/latest-version/	Reference map of irrigated areas	Area equipped for irrigation per cell

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